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Research

Toward understanding the governance of varietal and genetic diversity

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ABSTRACT. Varietal and genetic diversity sustain modern agriculture and is provided by breeding systems. Failures in these systems may cause insufficient responses to plant diseases, which threatens food security. To avoid these failures, an understanding of the governance challenges in providing varietal and genetic diversity is required. Previous studies acknowledge the complexity of seed breeding, framing the discussion in terms of rivalry and excludability. We consider breeding systems as social-ecological systems that focus on activities that generate varietal and genetic diversity and their adaptive ability. We use an inductive approach based on qualitative methods combined with the social-ecological system framework (SESF) to depict how highly context-dependent German winter wheat breeding, multiplication, and farming activities are. Our results show that the challenges for governance lie in providing credible and symmetric information on variety performance to all actors. This is the means to steer actors into collective action by subcontracting, buying, or saving seed. Based on our application of the SESF to the German wheat breeding system, we propose to develop a more general, sectoral SESF for the sustainable governance of plant breeding by offering an adaptable template for analyses of seed systems in other contexts.

Key Words: *genetic diversity; new institutional economics; plant breeding; seed production; social-ecological systems framework*

INTRODUCTION

One of the greatest challenges to modern agriculture is increasing productivity while using fewer resources and reducing negative environmental impacts (Rockström et al. 2017). Plant breeding seeks to improve the crop varieties used for agriculture (Becker 2011) and has contributed to increasing yields, especially over the last 100 years (Huang et al. 2002, Evenson and Gollin 2003, Qaim 2020). Although intensification reduces land expansion, the increase in land productivity is accompanied by environmental damage through the use of chemical fertilizers, crop protection agents, and other yield–enhancing inputs (Pretty 2018). Nonetheless, plant breeding is expected to further generate land- and resource-saving growth of yields, increase pest-resistance, and consequently ease the trade-off between food security and environmental impacts.

Seeds are not only an input but rather a technology shaping agricultural systems. For example, farmers will be more successful at sustaining organic cropping if their seeds are resistant to those pathogens handled by chemical crop protection agents in conventional farming (Denison 2012). Breeding systems supply farmers with a choice of seed varieties, which allows them to pick those that best fit their specific biophysical conditions (climate, soil, pest, and weed pressures), their cropping system, and other preferences. New varieties, however, need to be created, multiplied, and then sold and used on farms. A breeding system therefore contains all those activities needed for creating new varieties to be used on farms. We see the breeding system as a social-ecological system (SES); i.e., a nested, multilevel system that provides essential services to society (Berkes and Folke 1998). The essential services refers to supplying genetic material and its corresponding information flows. Genetic material refers to allelic snippets (variants of genes at gene loci), genetic traits (aggregation of specific allelic combinations), breeding lines (aggregation of genetic traits in plants over several generations), experimental cultivar variants, and varieties in the form of seed. For the purpose of our discussion, we limit ourselves to appropriating and provisioning activities of genetic material by breeders (creating new varieties), multipliers (multiplying seed), retailers (selling seed), and farmers (using the varieties in cropping).

Plant breeding is defined as "the creation, selection and fixation of superior plant phenotypes in the development of improved cultivars" (Moose and Mumm 2008:969). A plant phenotype is the observable outcome of the genetic combination of different alleles of a plant under environmental conditions. Breeders can create new varieties only if they select an improved combination of traits. However, they will be able to select this combination of traits only if there are pre-existing allelic combinations in the genes that are capable of producing the desired traits. Therefore, breeders can create a wide set of different varieties, using combinations of different traits, only if they have genetic variation in their breeding material. This is called genetic diversity. Varietal diversity refers to the variation in the set of available varieties.

Genetic and varietal diversity is crucial to maintaining or increasing yields and providing other desirable traits. Historically, epidemics of plant diseases have destroyed entire harvests and slashed yields to a minimum. The black rust epidemics in 1904 and 1916 reduced the wheat harvest in the U.S. Great Plains to one-tenth of its previous yield (Salmon et al. 1953). Governmental intervention and the existence of a few cultivars with disease-resistance genes prevented further dramatic yield losses (Salmon et al. 1953). Today, once again, world food security is threatened by plant diseases, such as Ug99, a new strain of black rust. This can potentially lead to a global plant epidemic with most severe harvest loss if not counteracted by improving diversity in resistance traits (Singh et al. 2011).

To prevent such disasters and maintain the overall functioning of breeding systems, we need to understand the opportunities and constraints faced by breeders, farmers, and other actors in the breeding systems. These opportunities, like the information a breeder receives in exchange for planting a colleague's material in one's nursery, or how multipliers subjectively think about the

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economic potential of a variety, are affected by the institutional arrangements structuring these situations. Like Ostrom (2005:3), we understand institutions as "prescriptions that humans use to organize all forms of repetitive and structured interaction (…) at all scales". These institutions, which are classified as rules, norms, or strategies (Ostrom 2005), channel the exchange of genetic material between breeders, the varieties contracted by multipliers, and varieties used by farmers. Regulating these human activities may lead to desirable or undesirable outcomes in social and ecological performance measures; for example, whether there are enough different varieties to choose from for cultivation. Likewise, the institutional arrangements determine whether a breeder possesses the right breeding material and incentives to produce new varieties. Therefore, the challenge for actors who craft these institutions arises in designing rules and considering existing norms such that varietal and genetic diversity can be maintained over time. Given these concerns, we attempt to answer the following question: What governance challenges arise for providing varietal and genetic diversity in breeding systems?

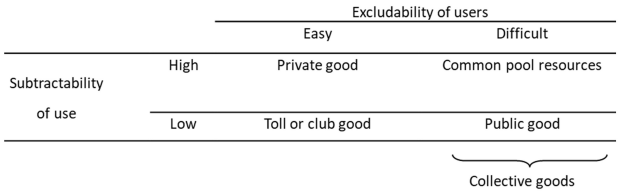
In the next section (*Breeding systems as social-ecological systems*), we motivate our general approach for using an SES perspective and point to literature that analyzes governance in breeding systems. As we look at breeding systems as SESs, we outline our ontological framework to identify governance challenges in the section *The social-ecological systems framework as an ontology for breeding systems*. Then, based on the social-ecological system framework (SESF) (Ostrom 2009), we explain that biophysical context determines activities in breeding SESs, and present three economic transaction theories, which we employ within the SESF. In the *Methods* section, we explain our operationalization of the elements of the breeding systems. Our results show for the case of winter wheat breeding in Germany how producing information on biophysical processes influences activities and governance challenges thereof. Here, we present the governance challenges for providing genetic and varietal diversity in breeding, multiplying, and farm-saving seed. In our discussion, we reflect on the need for resilient seed systems. We present our hypothesis on trust and biophysical information and how this ties together with future crafting of mid-range theories and potential uses for a seed sector SESF. In our conclusion, we summarize our findings and propose further testing of our hypothesis.

Breeding systems as social-ecological systems

Motivation for general approach

We motivate the general approach addressing our research question in the remainder of this introduction. The literature on governing breeding activities frames breeding material, traits, lines, seed, or innovation in seed in terms of two attributes—"subtractability" and "excludability of users" (Fig. 1). Subtractability refers to the extent to which using a good or service will reduce the availability of the good or service to others. Excludability relates to the difficulty of restricting other users from harnessing benefits of a good or service being provided. Collective goods subsume all goods and services with nontrivial cost of exclusion. These two attributes imply that resource units are merely physical subunits of a resource stock. Most researchers acknowledge that individual resource entities from plant breeding systems are multifaceted and do not fit this goods typology. They draw their readers' attention to different aspects of seed materials, such as the constructed cultural resource component of plant genetic resources (Halewood 2013), the informational component of seed breeding (Brandl et al. 2014), the public good attributes of plant breeding research (Brandl and Glenna 2017), or intellectual property rights assigned to seed developed (Godt 2016). Sievers-Glotzbach et al. (2020) provide an overview of literature on the different forms of seed commons in recent years.

Fig. 1. Typology of goods and services adapted from Ostrom (2005), including definition from Hinkel et al. (2015).



Despite these concerns of lacking categorical fit, most studies use a good or service as the vantage point for their analyses. Hinkel et al. (2015) emphasize that no resource is rivalrous or excludable per se, but rather is dependent on the activities related to the respective resource units. For example, it is important to differentiate whether people are engaged in recreational fishing using catch-release, or if fishing is a source of food, which remove their catch from the resource system.

In breeding and farming, it is difficult to exclude stakeholders from seed saving and infinitely farm-saving seed. If the cost of exclusion from the benefits of a good or service are nontrivial, then we define these as collective goods, as in Hinkel et al. (2015). Hence, we classify seed material as collective goods, which necessitates the specification of the degree of subtractability of the good along specific activities. Each activity in an action situation should therefore be considered on its own in how it subtracts units from a resource stock. Action situation denotes the metaphorical space where activities of actors occur. For details, we refer to Poteete et al. (2010:40).

Taking an activity-focused perspective, however, opens up the possibility to (a) diagnose in what action situations subtractability is relevant, and (b) unpack the attributes adding to the underlying social dilemmas of the action situations. We show how to possibly define the resource system and resource unit context to determine how their attributes influence subtractability in action situations that provide genetic and varietal diversity.

Furthermore, the activity-focused perspective allows us to explore government options in a more differentiated manner. Formerly, an ideal form of government was associated with different kinds of goods as a panacea for failing resource management (Ostrom 2010*b*). Usually, a free market was deemed ideal for private goods and a hierarchical government for public goods. Yet, these ideotypes of governance prove impractical when looking at context-dependent situations like governing agricultural research for seed innovations (Brandl and Glenna 2017).

Policy-makers need a clearer idea of which activities to regulate under what conditions. Crafting effective policies needs midrange theories, which account for context but still are generalizable to

multiple variants of the same subject of governance. For example, different kinds of breeding, such as conventional, organic, or participatory breeding (Chable et al. 2008), may exist under the same regulatory schemes. These schemes need to accommodate for breeding of fruit (Wolter and Sievers-Glotzbach 2019), vegetables (Chable et al. 2008), and grain (Gerullis 2016), although the individual types of crops pose very different challenges when being improved by breeders. To develop theories fit for effective governance, we need to provide a baseline to be capable of saying how the current systemic configuration functions. Looking at resources from the usual dichotomous perspective may lead to panacea prescriptions of governance rather than to context-dependent heuristics of governance (Darnhofer et al. 2010).

We tackle these mentioned deficits in conceptualizing the breeding system as a SES and analyze its governance challenges. We apply the SESF developed by Ostrom (2009) and McGinnis and Ostrom (2014), taking an activity-focused analytical perspective. The SESF is the only SES framework that puts equal weight on the social and ecological system (Binder et al. 2013). It was developed with a focus on sustainable outcome performance of governance-related research questions (Poteete et al. 2010, Binder et al. 2013). We want to establish a starting point for developing future midrange theories that serve the sustainable governance of breeding systems. To effectively do so, we present where the current governance challenges in seed breeding occur and how they are tackled by different coordination mechanisms in industrialized plant breeding systems.

We apply the SESF to German winter wheat breeding because it poses an instructive case: winter wheat is one of the most produced cereals worldwide and in Germany. Wheat is a self-pollinating crop, which makes it an archetype of line breeding—the most popular technology in breeding cereals throughout the last century (Becker 2011). Wheat has a high productive value for German farmers and breeders. The German wheat breeding sector comprises 21 active breeders. Thus, the case of German winter wheat lies in-between crops that are bred in a setting of high market concentration, such as maize, and small, localized breeding activities, such as legumes. We expect the case of German winter wheat to be highly instructive as a large-scale agricultural resource system with a variety of different attributes.

The social-ecological systems framework as an ontology for breeding systems

This subsection presents the ontological framing of our analysis, the SESF, and underlying premises—resilience of SESs, social dilemmas, and governance challenges. Ontology means the essence of reality (Poteete et al. 2010:216), and an ontological framework is a guide to arrange essential features of complex systems, like SESs. The SESF is used to include the underlying structure of SESs around an underlying action situation where activities are governed to solve (or not) a social dilemma. Yet, one needs theories to connect the systems' entities meaningfully.

Our premise is to treat breeding systems as SESs. Resilience—defined as the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Walker et al. 2004:4)—is the underlying desired goal. Therefore, we stress the importance of (a) maintaining the link between social and ecological systems, and (b) maintaining the defining system functions. Our research question in this context is how does the breeding system provide genetic material flows such that food and fiber for human consumption can be sufficiently supplied while maintaining ecosystem service provision from connected ecological systems? As such, the provided flows of genetic material, mainly in the form of seed, need to fit farming purposes to ensure varieties are adapted to specific ecological contexts and farming objectives.

That is, for individual cropping and breeding systems, maintenance and function is context-dependent because each cropping system has different configurations and attributes of social and biophysical entities. However, for different types of breeding systems, the capability of providing functions and the desirability of outcomes needs to be assessed (Carpenter et al. 2001). The SESF serves as a tool capable of arranging different system parts into a framework with the underlying focus on the performance of governance (Poteete et al. 2010, Binder et al. 2013).

Social dilemmas arise when individuals are tempted to take an action but the collective will be better off if all (or most individuals) take other action(s) (Poteete et al. 2010:79). As outlined, nontrivial cost arises from keeping someone from undertaking undesirable activities, termed as the cost of exclusion (Hinkel et al. 2015). Collective goods are a category of dilemmas where these costs arise from undesirable appropriation activities. If some actors overuse a resource, those activities may then reduce other actors' potential use. In its extreme form, this may lead to the unrecoverable overuse of a resource and a collapse of the resource stock. The governance challenge is to implement institutional arrangements such that (a) activities of appropriating a collective good will not overuse it, and (b) the collective good in question will be created, maintained, and improved over time. The first is a canonical appropriation action situation, while the latter signifies the canonical provision action situation (Hinkel et al. 2015). Different factors influence the core relationship of individuals solving a social dilemma. Solving a social dilemma usually entails some form of collective action or cooperation in activities of individuals. Cooperation among individuals is highly context-dependent (Poteete et al. 2010). In the SESF, we separate the context into a micro-situation, identifying attributes that directly affect individual behavior and broader social-ecological variables.

The premise for using the SESF is that we can unpack influencing factors of activities in a hierarchical manner. The SESF by design allows for using different theories within the same framework, making it possible to compare the economic coordination mechanisms currently regulating the different material and information flows within the breeding system. There are many entities, system features, interactions, and feedback loops that can be aggregated and disaggregated to concepts that influence the outcomes of activities in a SES. We assume that these variables are subsystems—one nested within the other (Simon 1996). Therefore, the SESF divides the underlying SES into different tiers.

The first tier of the SESF comprises the resource units as part of the resource system. The resource units function as inputs to the action situation, and the governance system defines rules for

actors participating in the action situation, with interactions leading to outcomes (Ostrom 2009). The second tier is most commonly represented as an extensive list of potential subconcepts of the various first tier concepts deemed relevant for the focal action situation. These concepts can further be subcategorized into more tiers if necessary. They will contribute by explaining how the micro-situation influences the behavior of individuals. We concentrate on those governance challenges regarding the links between the social and biological domain connected to the appropriation and provision activities of the collective goods in question. Therefore, we concentrate on breeding, seed multiplying, and seed-saving/seed buying activities.

Biophysical context

The SESF has been developed for analyzing the governance of small-scale resource systems. Likewise, the design principles from Ostrom (1990) inform the sustainability of small-scale resource systems. Projects like the Social-Ecological Systems Meta-Analysis Database (SESMAD) (Cox 2014) explore sustainable governance of large-scale resource systems. Breeding systems of whole countries—as in our case—are large-scale resource systems, since they go beyond one spatially well-defined area and include several soil–climatic niches (Acquaah 2007, Cox 2014). For the sustainable governance of large-scale natural resource systems, findings and theories are not yet available to serve as design principles (Ostrom 1990). Partelow (2018) suggested aggregating insights on different resource system types into sectoral SESFs for finding the context-dependent unique yet shared variables of different natural resource types, such as fisheries or forests.

In the SESF, biophysical entities are segregated into resource system and resource units, which aggregate to a resource stock. The classic example is a fish being one unit of a fish stock, and the underwater ecology and all the technical infrastructure (e.g., fishing boats) to provide the fish is the resource system. Varietal and genetic diversity are idiosyncratic resources in the sense that they are both dependent on human activities and need to be sown, managed, and actively improved by humans. Changes in crop seed attributes will be produced only if humans actively change the nature of a plant. Degradation of varietal and genetic diversity stems from not undertaking the respective activities. Not sowing a variety will lead to the disappearance of its genetic or phenotypic traits and its loss from the common gene pool or varietal stock. Hence, seeds are biofacts (Karafyllis 2006), meaning they are biological material, a natural resource, and a (human-designed) technology at the same time.

Moreover, the "quantity" of our resource stock (pool of varieties or gene pool) is the difference in traits and not the mere number of varieties or genes present. "More" genetic material or varieties is not superior to "less" material, but whether the material at hand can satisfy the needs of human end-uses is decisive. From an economic perspective, varieties are bundles of attributes where each farmer or breeder has a unique satiation point for a specific combination of attributes compared to bundles that deviate from this ideal combination (Varian 2006). Therefore, the governance challenge for varietal and genetic diversity is to steer the community of actors to continuously use seeds such that a desirable set of traits is available despite potential individual incentives to behave otherwise.

Theories of transactions

We are not interested in the SESF as a mere descriptive collection of variables, but want to inquire about how biophysical features connect to the social system. We want to know how processes that create biophysical information influence the coordination mechanisms of human-nature transaction in the relevant action situations. We base our choice of theories about these connections on the descriptions of our interviewees and on how secondary literature frames the respective activities as (1) cooperative undertaking of material exchange between seed businesses (Gerullis 2016, Brandl and Glenna 2017; observation 1, 2, 12, 19, 22, 23), (2) contracting and subcontracting in seed multiplication (Thiel 2014; observation 3 and 4), and (3) "the seed market" (Brandl et al. 2014; Braun 2020; observations 1–9). We use economic theories of transaction to show the disparity in what is relevant for coordination mechanisms to function from the perspective of the economic ideal and what actors identify as relevant. This also justifies our use of the SESF, as it was designed to accommodate multiple theories in one framework and makes them comparable with respect to the scrutinized entities. Hence, we analyze the relevance of the theories in the context of the coded action situations.

We compare the theories of transaction with our observations based on Ostrom's (2010*a*:161) "broader theory of human behavior". Ostrom (2010*a*) outlines how trust and reciprocity, apart from behavior like norm adoption or learning, will lead to a higher or lower likelihood of self-organization of the actors involved in a social dilemma. As we look at activities in coordination mechanisms that allocate resources to observe how individuals deal with (potential) social dilemmas in human-nature transactions, we show how reciprocity and trust are steered within coordination mechanisms in markets, individual contracting, and collective action through social norms (Ostrom 2010*a*, Potetee et al. 2010).

Standard market theory assumes that prices are the only market signals driving the behavior of actors participating in transactions, and that competitive markets deliver economically efficient results (Levacic 1991). Producers and consumers are brought together in a mutually advantageous exchange of goods or services, and diverging interests are resolved through a price on which both parties agree (Callon 1999). Owing to the structure of market transactions, actors in markets are able to put their trust in the system itself rather than into other parties involved in the transactions. Because the transaction in a market is near instantaneous from the moment an individual enters the transaction to its fulfillment, there is no reciprocity or reputation building taking place in this setting. Both parties can leave the market transaction without lasting ties, as strangers to each other (Callon 1999).

Collective action gives stakeholders a chance to manage the natural resource system sustainably. It provides the option of using the resource over an infinite time horizon if they choose to bear the cost of self-organizing. Reputation, trust, and reciprocity play major roles here, where different structural variables such as the number of participants, face-to-face communication, heterogeneity of participants, or past experiences influence these three concepts and their linkages, thereby leading to different levels of cooperation. For a more extensive list of these variables,

see Poteete et al. (2010:228–232). Natural resource systems usually bring about their resource units with a time lag and in very different forms. While in a market, all activities regarding the appropriation of goods and services can be transferred into money equivalents (Callon 1998), not everything a natural resource system produces can be calculated in one type of (metaphorical) currency. Trust and the entanglement in dependencies from other actors bridge structural and time differences of the transactions taking place. Moreover, the time lag gives actors the chance to reciprocate and frame these activities as seemingly selfless (Callon 1998), expressing trust and building more personal bonds between individuals, such as friends.

Subcontracting occupies a middle ground between market and subcontracting settings. Its time horizon is finite but not instantaneous. There is usually a time gap between the fulfillment of one party's obligation and the return of the service/good by the other party. Both individuals cannot part as strangers before both sides receive their due, but neither can they rely on a lasting bond to balance any open account. They may specify their mutual obligations in a contract, configuring every little detail of the relationship through bargaining, negotiations, and mutual adaptions (Lorenz 1991). Again, the underlying challenge is to collapse time frames and goods or services exchange into one contract, even though they are delivered with a lag and in (potentially) different forms. Such specifications, be they written or merely verbal, are however limited by the underlying transaction cost involved in bargaining, negotiation, and adaption processes. Not all actions can be sufficiently controlled or monitored, even if they are set in writing within a contract (Lorenz 1991). For the duration of a contract, the involved actors are thus neither strangers nor friends to each other but are locked into reciprocation and trust over a negotiated time horizon.

METHODS

This section lays out how data for the German winter wheat breeding sector case were gathered and how we operationalized the SESF for unpacking the micro-situations around breeding, multiplying, and seed-saving activities. We took an inductive approach in our research design (Bernard 2013) to accommodate for a wide variety of data types: (a) qualitative interviews, (b) participant observation, and (c) secondary sources from scientific literature or practical guide books on breeding, farming, and seed multiplication.

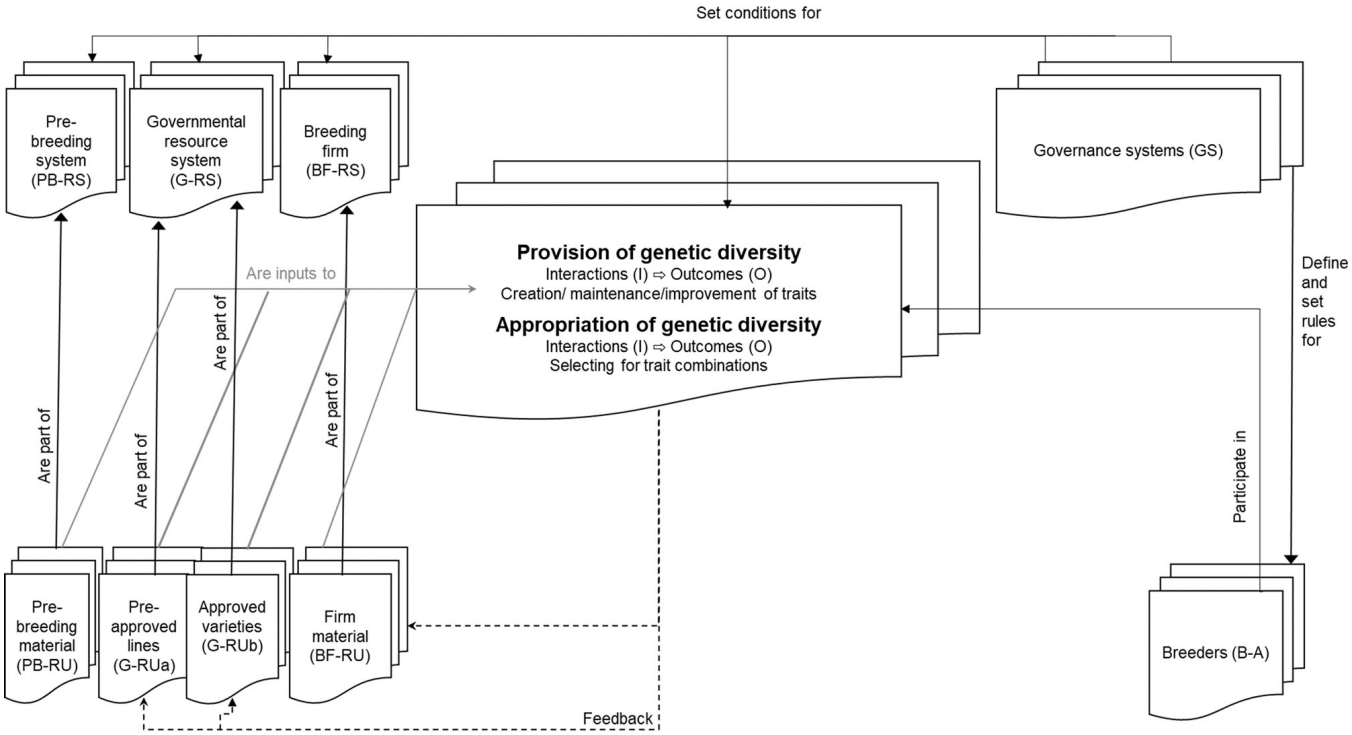
Data collection followed a grounded theory style process (Bernard 2013), as plant breeding is very heterogenous in terms of explicit and implicit knowledge (Timmermann 2009, Brandl et al. 2014). Strauss and Corbin (1994:276) state that "the methodology's central feature is that its' [sic] practitioners can respond to and change with the times (…), as conditions that affect behavior change, they can be handled analytically". We conducted qualitative, initially open and later semi-structured interviews with open questions. To avoid misrepresentation of individual attitudes and viewpoints, interviewees' claims were anonymized, fed into modified questionnaires, and then presented to subsequent interviewees for comment. Through this iterative approach, we consolidated individual perspectives into a knowledge consensus of the plant breeding community. To account for survivor bias and sequentiality, these consolidated accounts were presented to the first round of interviewees for validation in a final feedback loop. Interviews were conducted throughout 2016–2017, with revisits on selected topics in 2019, on four occasions (see Appendix 2, Table A2.1 for a detailed listing of topics). During the 2019 round, we sought mainly to update information in the face of changes in the industry (pathogen disease events, merges and acquisitions, business trends) and to complete information missing from earlier accounts. Our 18 interviews were complemented by participant observations on 21 occasions (see also Appendix 2, Table A2.1). We used participant observation to supplement our interview data with practical, first-hand experience of processes in breeding programs (Bernard 2013). All quotations were translated from German into English.

Interviews and participant observations are numbered in brackets following each paragraph. Information on retailing and multiplication was drawn from secondary and legal sources as suggested by Cox (2015) to complement case study work on SESs. Our initial access to winter wheat breeding came from contacting two private wheat breeding firms: a southern Bavarian cereal breeder and the other from Lower Saxony in northern Germany. This allowed us to sample further interview partners in both regions through snowballing (Bernard 2013). Because southern Germany has smaller spatial segments in its ecological niches compared to northern Germany, we wanted to account for potential differences.

There is less market concentration in German winter wheat breeding compared to other crops such as maize or rapeseed (Brandl and Glenna 2017). German plant breeding is done by 58 different private businesses that produce commercial seed, of which 21 have winter wheat programs. Public research centers support German agricultural extension to farmers and conduct research projects with breeders. The Federal Research Centre for Cultivated Plants and the Bavarian State Research Center for Agriculture are prominent actors at the federal and state level, respectively. Both institutions support public plant breeding through public–private partnerships (Brandl et al. 2014). The employees of governmental organizations are usually referred to as "public breeders", although producing new varieties is not their main goal. Instead, they provide public infrastructure for variety trials and pre-breeding programs.

Interview transcripts were initially coded openly (Bernard 2013). In the subsequent step, we used the diagnostic procedure by Hinkel et al. (2015) to determine underlying social dilemmas and the different entities of the SES to ensure comparability with other SESF cases. These codes were conceptually matched with the SESF variables, for which the results can be seen in Figs. 2–4 for the first tier and in Appendix 1, Figs. A1.1–1.3 for the second tier. Hinkel et al. (2015) provide a set of 10 questions to identify and interpret the different attributes of the units of the resource (RU) and their providing resource systems (RS) together with the action situation and governance system (GS) from the SESF. RU and RS were codified as suggested by Hinkel et al. (2015) to characterize governance challenges in relation to two types of action situations: one is a provisioning action situation in which certain actors face the collective challenge to maintain, create, or improve the collective good; the other is an appropriation action situation in which actors face the collective challenge to avoid overuse of a collective good. We use the identified actor groups, RU stocks, and RSs in the following for representing the first tiers

Fig. 2. First-tier social-ecological system framework components for provisioning and appropriating genetic diversity.



First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 1, 2, 3, 7, 8, 10, 12-15, 17-20, 22, 24-30, and 32; see Table A2.1.

of the SESF in breeding, multiplication of seed, and appropriating seed by seed-saving or seed buying (Figs. 2, 3, and 4, respectively).

There are shortcomings to our approach. Our sampling through snowballing from those breeders in our vicinity may have introduced a bias to a certain degree, as we were not able to interview breeders from one of the firms dominating the international seed market, such as Bayer Crop Science or Syngenta. Moreover, the heterogeneity of the data posed a challenge in terms of integrating them into the SESF, and would not have worked without Hinkel et al. (2015). Yet, we are still missing a proper diagnosis to operationalize the GS variables of the SESF in correspondence to the RS.

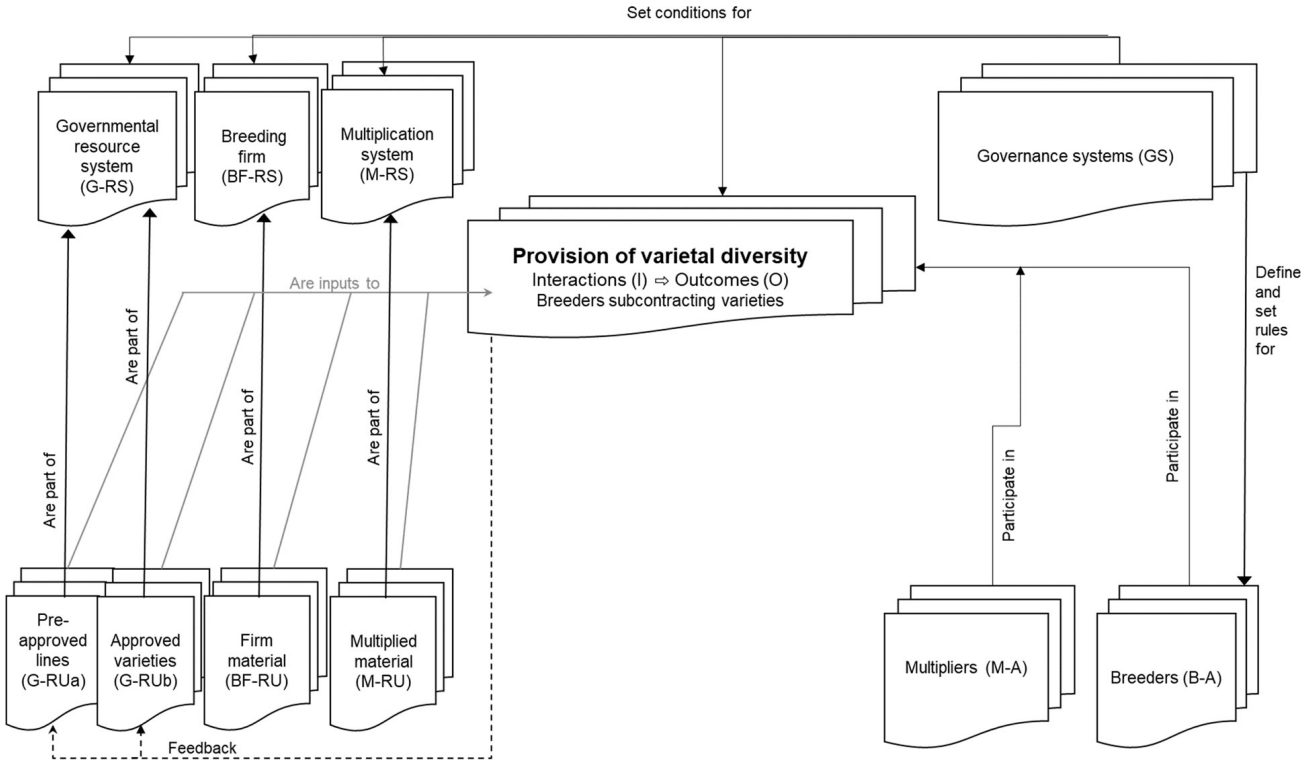
RESULTS

This section presents the results of using the SESF for German winter wheat breeding. We present the governance challenges arising from breeding, multiplying, and using seed for farming. The three action situations show how social dilemmas in breeding systems depend on how information on biophysical context is created and distributed. In Fig. 5, we provide an overview of the main activities in the breeding system, comparable to the examples provided in Hinkel et al. (2015). Fig. 5 shows which and how different activities contribute to the two outlined provisioning situations. Each activity–to–RU relationship yields different levels of subtractability.

In this section, terms in parentheses refer to variables or entities in Figs. 2, 3, 4, or 5. Second-tier SESF variables—also in parentheses—are preceded by two letters that indicate the corresponding entity they refer to in the corresponding first tier. They can be found in Appendix 1, Fig. A1.1 for appropriating and providing genetic diversity, Fig. A1.2 for providing varietal diversity, and Fig. A1.3 for appropriating varietal diversity.

Varietal diversity is crucial to the farming system because the available variation enables farmers (F-A) to choose the variety appropriate for their needs. The main benefits to farmers from cropping a variety are the security and income derived from stable and high yields over the years. In Germany, farmers will buy varieties listed on the Descriptive Variety List from agricultural retailers (R-A) if they do not save seed on their own. Breeders subcontract rights to multiply varieties to multipliers and retailers through different licensing relationships, involving marketing organizations and other governing actors (GS). Breeders (B-A) and multipliers earn income through license fees from selling varieties to farmers. For retailers, seeds are merely one input among others sold to farmers. Breeders have a future value from a diverse gene pool available for their breeding activities. Breeders supply the initial material from which multipliers propagate the marketed seed (M-RU). In Germany, breeders receive licensing fees for sales of certified seed and for farm-saved seed (F-RU), which farmers voluntarily pay to a (private) governing organization, called *Saatguttreuhand*, which reimburses breeders for these seeds [1, 3, 4, 6, 11].

Fig. 3. First-tier social-ecological system framework components for provisioning varietal diversity.



First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 1, 2, 3, 4, 6, 8, 9, 14, 21, 23, and 33; see Table A2.1.

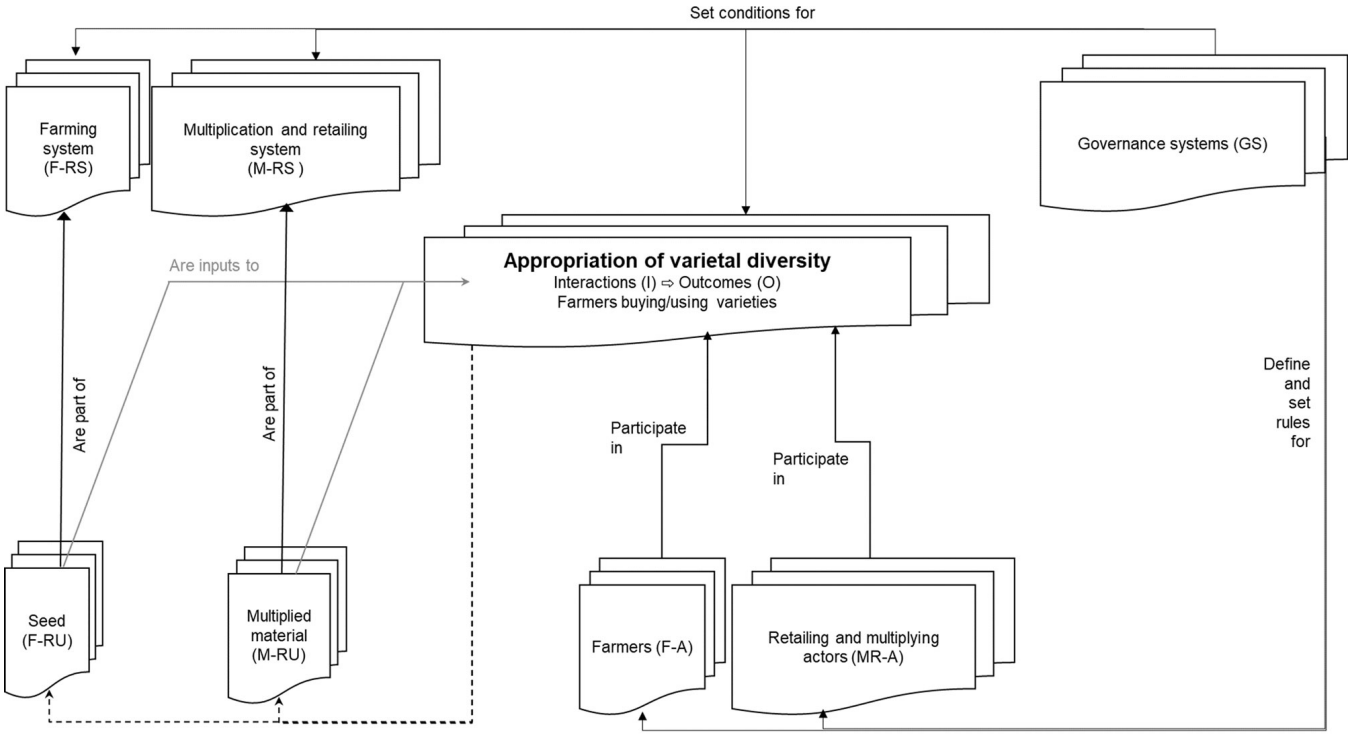
Providing genetic diversity

To develop new varieties, breeders need genetic variation in different candidate cultivars. Next, they select those candidate variants from the plots of the candidate cultivars, which are planted for inspection, with desired observable traits under different environmental and management conditions (Becker 2011) (see Fig. 2 [first-tier variables] and Appendix 1, Fig. A1.1 [second-tier variables]). Having data on agronomic traits for different genotypes is central to decision-making in plant breeding —"the data [are] key" [27]. The different input materials are marketed varieties (G-RUb), pre-approved lines (G-RUa), pre-breeding material (PB-RU), and a breeding firm's own material (BF-RU). Asked whether there is a global gene pool, one breeder responded, "no no no…the gene pool is what [breeders] build up themselves, each unique to themselves—the employees and the breeders. There are breeders who always register the same variety type, because they believe that's how a variety needs to look like —their ideotype. There is a gene pool of the individual breeder, which is there. And it depends upon philosophy of the breeder how far he wants to break that up—and for what target market he is breeding for" [2]. Breeders' gene pools therefore depend heavily on their decision-making.

Breeders tackle two main types of decisions: crossing, and selecting for a targeted genetic and phenotypic variation within their material (Timmermann 2009). Depending on the size of a firm's breeding program, this potentially involves planning a hundred to several hundreds of crosses per year. Selecting variants deemed as good candidates for varieties (positive selection) or not worthwhile keeping (negative selection) means inspecting several thousand variant plots per year (Timmermann 2009). Based on the information available on agronomic performance data and its quality, breeders decide which genotypes to use for crossing and during selection (GD-I1) [1, 2, 10, 17, 18, 19, 26, 27, 28, 29, 30].

Time, nursery space, and information on material are scarce in the breeding process. Information on traits is produced by sowing, inspecting, and harvesting the different materials in different testing sites and nurseries sustained by the breeding firms (BF-RS) and different governmental organizations (G-RS; PB-RS). Time is critical in breeding because it takes on average 12 years to establish a desired trait combination in a variety. The size of nurseries determines how much space there is each year for inspecting their different lines. Nurseries together with greenhouses, cooling chambers, and all other required technology elements make up the resource system's size (BF-RS3) and determine the number of candidate varieties (lines) submitted for approval. While big firms will have multiple locations around the world to test their breeding material (BF-RS9; BF-RU7b), and greenhouses, big nurseries, and the newest technological setup (BF-RS4; B-A9), small- and medium-sized breeders lack capital for such equipment, thereby leading to heterogeneity among

Fig. 4. First-tier social-ecological system framework components appropriating varietal diversity.



First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 4, 5, 9, 11, 8, 16, 21, 23, 31, and 33; see Table A2.1.

actors in their socioeconomic attributes (B-A2) [1, 2, 10, 26, 27, 28, 29, 30, 12, 13, 14, 15].

Breeders employ different strategies to increase their selection pressure. One is to have multiple nursery sites to test breeding material throughout the year. Multiple testing sites can gather rich data on variation in cultivar performance under different biotic and abiotic conditions (Becker 2011). Another strategy is to exchange information (GD-I2a), material (GD-I2b), and nursery space (GD-I2c) at different sites with colleagues or to cooperate in research projects (GD-I5) [1, 2, 29, 30].

In anticipation of the spread of public information, breeders will share their information and material on a bilateral basis before they are obliged to do so by law. Breeders usually have bilateral contracts with their colleagues that give each other access to their pre-approved material (G-RUa), which gives them the opportunity to cross-in material of colleagues 1 or 2 years ahead of time. This leads to a spillover of traits between different firms and spreads attractive traits throughout all firms' gene pools. Most breeding firms cooperate in research projects (PB-RS) and with public breeding programs (PB-RS) to conduct research for introducing more exotic material (GD-I7/8). These projects give breeders the opportunity to circumvent lengthy and costly screening and back-crossing activities with non-adapted material, the so-called pre-breeding material (PB-RU). It can take up to 30 years until certain traits of genetically distant material are transmitted into adapted material, carry the desired traits, and exhibit the same yields as adapted varieties [1, 29, 30, 25].

Governance challenges of providing genetic diversity

The governance challenge in providing genetic diversity (GD-O2) originates in supplying and using an ample set of different genotypes to/by breeders (GD-O1; GD-I1). The potential social dilemma for genetic diversity is that no variation is left to cross with, which reduces the scope for improvements in agronomic traits. One of the interviewed breeders uttered this concern: "You know, people say—and that is actually a bit frustrating—that today there is only 5% variation left in the wheat genome [in Germany], the rest is fixed, because these are positive traits, which are the same for all varieties…and that is a considerable narrowing.…Germany's [wheat] gene pool has a quite close degree of [pedigree] relationship" [2]. The underlying problem here is that breeders may mainly be crossing-in those traits that are easy to cross-in but not those traits that need more breeding effort to enter a gene pool, although they might be necessary for long-term desirable cropping systems (All-RU3; GD-O2). In cereals, "quantitative resistances against diseases [exemplify] difficult-to-breed-for traits" [24]. Quantitative resistance traits depend on multiple gene loci, and therefore will not be breached as easily by pathogens. Establishing quantitative resistance traits in combination with high yields is difficult for breeders and can be the effort of "a whole career" [1]—"40 years" [2]. It is easier to take qualitative traits with known single gene loci and cross them into one's material, aided by genetic markers. Yet, these are "easily breached" [24] by pathogens.

Fig. 5. Overview of provisioning action situation for seed production of German winter wheat based on the diagnostic procedure from Hinkel et al. (2015).

Collective Goods	Actors	Benefits	Activity	Stock of RU	Subtractability	Ressource System	Provisioning Action Situation
Diverse set of genotypes = genetic diversity	Breeders (B-A)	Future value of a genetically diverse system	Pre-breeding	Rest of primary genepool	Low	Techniqual facilities and nurseries used for pre-breeding (BF - RS)	Breeders maintain well-performing varieties, which they supply, adapted to the current conditions by ensuring a sufficiently diverse set of on-nursery-genetic diversity to select from
				adapted breeding material to temperate German climate	Medium		
		Income from licenses of Z-Saatgut and income from resowing licences	Creating /maintaining /improving inhouse variation	Lines submitted to trials for value of cultivation and use	High	Testing sites for value of cultivation and use trials; machinery and other infrastructure involved in the cropping process; governance expenditure used for the testing; calculating power for data processing (BF - RS)	
				All available varieties on Descriptive Variety List	Low		
				Diversity of genotypes and knowledge about internal lines within individual breeding firm	High	Nurseries; machinery; laboratories anything technical or subcontracted by the individual breeding firm (G - RS)	
			Selecting from inhouse variation		High		
			Subcontracting varieties to multipliers/ agricultural retailers	Total expenditure of agricultural retailers / multipliers	High		Multipliers / retailers supply a set of varieties fitting different ecological niches and preferences of farmers
Diverse set of varieties = varietal diversity	Multipliers (M-A)	Income from sublicensing of certified seed and income from selling multiplied seed to breeders/retailers	Selling certified seed to agricultural retailers	Total expenditure of agricultural retailers	High	Farming equipment for sowing, growing, harvesting seed (M – RS)	
			Multiplying seed for breeders	Total expenditure of breeders for licensed activities	Medium		
	Agricultural Retailers (R-A)	Income from selling other inputs	Selling certified seed to farmers	Multiplied seed	High	Storage equipment for storing and selling seed (M – RS)	
		Income from selling seed	Selling fertilizers and pesticides matching the respective seed	Farmers total expenditure	Low		
	Farmers (F-A)	Income from selling one's yield	Conventional/organic winter wheat cropping	All available seed	Medium	Farming equipment for sowing, growing, harvesting seed (F – RS)	
		Security from stable yields over the years		Other inputs to farming			

Breeders exhibit the attributes highlighted as tentative for collective action (Ostrom 2010*a*). They improve, maintain, and use their material within self-organized research projects. They also set informal norms for their activities within the community. The targeted activities create new candidate varieties using the RUs under scarce space, time, person-power, and nursery locations. Inspecting material "at a colleague's nursery" [29], or even when they will inspect it for each other, means that one has more information to base one's decisions on as a breeder. Mutual trust and reciprocation in individuals (Burt et al. 1980) play vital roles here because one party needs to trust in the other to use and allocate resources toward their colleague's material "which others will exchange with you" [30] in the long run. They cooperate with each other in activities over a 45-year time horizon. They share material and corresponding information or participate and share investments in public–private research projects on costly traits. All of these activities are undertaken based on trust between the individuals and the reputation they build over time (B-A6). As such, the governance of breeding material for German winter wheat complies with collective action theory (Ostrom 2010*a*) [1, 2, 31].

The German governmental system (GS) symmetrically supplies information on qualities and agronomic performances of all lines submitted for public approval (G-RUa6; G-RUb6) to all participating breeders (B-A1; GD-I2a), as a benchmark of "seeing the performance of the competition" [7], and aids in research of "hard-to-get-to" [25] traits, which may demand more breeding effort than usual crop attributes. Yet, trust is supplemented by information. Symmetric information is a key feature of the transaction relationship between breeders. The information on the cultivars' (RUs) performance of qualities and agronomic attributes are key signals to a breeder's decision process on which material to use for breeding (GD-I1)—"if I see something good in the material [of others'], I will cross it in right away" [29]. Public information provision is key because it supplies breeders with the same comparable information and facilitates early exchange of material among breeders [1, 8, 24].

Providing varietal diversity

Providing varietal diversity depends on breeders successfully subcontracting variety multiplication (see Fig. 3 and Appendix 1, Fig. A1.2) and marketing seed to farmers (see Fig. 4 and Appendix 1, Fig. A1.3). Farmers (F-A) may sow three types of seed: farm-saved seed, certified varieties used before, and certified seed from a new variety (Heisey and Brennan 1991). The proportion of newly bought (M-RU) compared to farm-saved seed (F-RU) is called variety turnover and determines the seed demanded. Seed turnover has been between 50% and 60% for German cereals in recent years, "with increasing tendencies" [23]. Turning toward buying certified seed depends on the value-added (F-RU4) and other advantages farmers receive from using certified seed (F-A7; F-A3), such as better germination qualities or forgoing "the hustle of dressing and pilling" the respective seed themselves (AV-I3; AV-I5) [5, 16, 21, 23].

Varieties are experience goods (Nelson 1970). If the yield from a new variety is not living up to its expectation (F-RS7), there is no

possibility to recover the damage. Farmers ideally pick those varieties that fit the biotic and abiotic circumstances of their farm (F-RS) and other preferences in yield and crop qualities (AV-O1; AV-O2). Farmers, however, may not pick optimal varieties with respect to their specific conditions. They choose varieties without resistances—sometimes because "a neighbor recommended [it]" [5,6]—and end up with applying more pesticides than necessary (Dachbrodt-Saaydeh et al. 2018), or they may have a short memory in picking their varieties because they "only consider the last year" [23]. If farmers, however, do not buy varieties with resistances, then those varieties will not have a market share big enough to be profitable for multipliers (M-RU4). Hence, multipliers abolish their multiplication (PV-I1), and the respective resistance traits will "cease from the existence" [24] of the set of varieties (PV-O1) [1, 2, 3, 6, 24, 31].

To forgo rent-seeking by retailing actors (M-A), public variety trials (G-RS) produce "unbiased" [9] information on how varieties perform in different trial locations as an orientation for farmers' variety choices (PV-I2). There is, however, a "varying supply of [public trial] information for [different] states in Germany" [9] (AV-I2). Some varieties "work well" [1, 2] across different soil–climatic regions and are a potentially significant source of yield and revenue (M-RU2; PV-I5). Some varieties are fit for more "specific regions" [6]—ecological niches. Varieties that perform well in a growing region (G-RS9; G-RUa) will be recommended for that soil–climate region and will be listed as such (see annual reports from the state variety trials, such as Nickl et al. 2018). State trial conductors will choose the varieties they deem fit for the individual regions, given the variety's characteristics in the national trials (G-RUb). They will for example "look at the [varieties'] performances in the diseases important for the region" [23] and then put those varieties into the state variety trials. Supply and demand of those varieties will therefore vary across different regions [5, 16, 23, 35, 9].

The appropriation situation is incorporated into the provisioning situation as the economic reasoning of the multipliers in providing varieties includes expectations on what farmers will buy later on. As holders of the plant variety protection rights (GS1; GS3; GS7), breeding firms are granted the right to multiply, prepare, and market seed material for a variety (§10 SortSchG (1985)—Plant Breeders' Rights Act). Breeders transfer these rights to multiplication and retailing businesses in exchange of licensing fees (Erbe 2002). Variety performance in national and state trials gives multipliers a first signal of how much a variety might be worth (AV-I2; PV-I2; M-RU4). This can have detrimental effects, as "one year [of bad performance] can destroy 20 years of breeding" [23], and multipliers will not buy the respective variety. Multipliers strive to have enough seed ready for sale in time. With wheat, it will take 3–4 years (M-RU2) of propagation until a reasonable amount of seed can be supplied (M-RS5; Becker 2011:33). Multipliers try to decide on which varieties to subcontract as early as possible (M-RU7a) [1, 2, 3, 6, 9, 23].

Governance challenges of providing varietal diversity

The governance challenge for providing varietal diversity is to coordinate an adequate supply of varieties multiplied and sold to farmers that fit their ecological needs and other preferences (PV-O1). For varietal diversity, the potential social dilemma is two-fold. First, farmers may not choose the varieties that fit their actual needs for many different reasons, which can lead to an underuse of certain traits (AV-O1). Second, multipliers may be prone to supply only "big varieties" [5] and abolish varieties that service small ecological niches or certain traits, such as resistances, due to lower revenue potential (PV-I1) [4, 35].

Both subcontracting variety multiplication and seed markets are forms of decentral coordination. Breeders subcontract the multiplication of their varieties to multiplying and retailing actors. Information on agronomic performance and baking qualities from public variety trials serve as signals on the attractiveness of a contracted variety to the involved parties (BF-RU4; M-A7). Farmers likewise take the information as signals for their decision on which variety to buy (F-A7; F-RU4; M-RU4) [4, 5, 35].

Trust plays multiple roles in seed marketing and multiplication. Seed marketing depends heavily on the trust farmers have in trial results. Retailer and farmer are per se strangers to each other and engage only in an instantaneous transaction relationship (Callon 1999). They may not trust each other directly, but both parties trust in the market system, establishing their private property rights over seeds purchased as a commodity (GS7) and qualities guaranteed by seed regulations and monitoring of multipliers and retailers (GS1; GS3) [21, 23, 32, 4, 5, 35]. Subcontracting of a variety establishes an expedient mutual dependency between breeder and multiplier. For the length of a contract, ranging from a few to 25 years, they are neither friends nor strangers (Lorenz 1991), and both parties do not reciprocate their actions beyond the contract. Levels of trust will, however, be influenced by the information supplied by public trials [6, 8, 33, 34].

Publicly supplied trial information produces different kinds of informational settings in both action situations. It brings about informational symmetry between farmers and retailers. This status cannot be reached for breeders and multipliers because breeders will always know more about the variety subcontracted because they have more information on a variety's descendance. Yet, the increase in information through official trials will provide the multiplier with enough information to enter a subcontract. Retailers have greater incentives to sell varieties that are susceptible to pathogens because they sell complementing crop protection products. Nonetheless, breeders need to trust retailers to fairly market their varieties next to varieties from competing breeders. Trust is expedient in this situation because one actor is incapable of monitoring the activities of the other properly. Hence, they enter a mutually dependent transaction relationship.

DISCUSSION

We presented a case of three different action situations (breeding, multiplication, farming) in a breeding SES and showed how three different coordination mechanisms direct human-nature transactions of winter wheat seed. We used the SESF as a tool to operationalize the different entities in the breeding SES, to ensure a systematic procedure that enables comparison with future cases of similar systems (Cox 2014, Partelow 2018), and to employ different theories within the same ontological framework. We showed how the production and distribution of biophysical information coincides with different forms of trust affecting transactions with different time horizons. For seed systems, the commonly employed economic theories may not bring about the relevant aspects for heuristics of governance in breeding, multiplication, and farming.

The production of biophysical information drives all coordination mechanisms involved. Where theory on markets of homogenous goods would suggest that the price is the only relevant signal, seeds prove to be a heterogenous good with limited fit to this model and to the narrative of their governance usually coming with it. Information on agronomic performance as communicated through public trial outcomes explicitly addresses this heterogeneity in seed and gives farmers, who are heterogeneous actors in heterogenous environments themselves, the possibility of finding a matching variety. Information on agronomic performances is key in stipulating actors in buying seed or seed-saving activities. Theory on collective action (Ostrom 2010*a*) describes processes in breeding well because it links biophysical information variables to activities. What breeding actors identify as key components of their activities converges with what theory suggests. Individual trust, reciprocity, and reputations play a vital role in breeding activities spanning long time horizons. Theory on subcontracting seems adequate in the role it attributes to expedient trust because it includes (agronomic) information signals for actors to engage in multiplying. However, further scrutiny into how subcontracting is influenced by spatial difference and the coinciding ecological niches is necessary here.

A hypothesis on trust and biophysical information

We propose that future studies examine the role trust and biophysical information play in enabling actors to coordinate their transactions involving natural resources in large-scale systems. Our hypothesis is that the credibility of information produced and the symmetry of supplied information are crucial for facilitating socially beneficial outcomes of the coordination mechanism. By informational asymmetry we refer to some participants in a transaction having more information on the resource system and units than others. The biophysical information of varieties—in wheat we consider 23 attributes commonly measured in trials (Nickl et al. 2018)—is of higher dimensionality than the price in Akerlof's (1970) classical example of the used car market. It signals the type of ecological niche the variety may fit. Therefore, our notion of symmetry or asymmetry of information refers to whole bundles of context-dependent information on varieties. Relevant for our hypothesis is whether it influences the trust relationship between the interacting individuals. Credibility of information is relevant and produced by joint public production and quality management of field trials (results over multiple locations and multiple variants). The state and federal variety trials produce unbiased information for all actors in the system. The relevant aspect for our hypothesis is whether one has trust in the process that produces the information.

Based on the information available to us, we cannot be sure whether trust in these situations works in a cumulative fashion and if different forms of trust could substitute for each other. Also, we cannot say if different forms of information each trigger different forms of trust and corresponding coordination mechanisms. If actors produce information "credibly" and supply it symmetrically, then transactions over material (in our case, seed) can be facilitated in a coordination mechanism where actors may part as strangers (Callon 1999)—in our case, a seed market. We suspect this may be due to individuals trusting in the market system rather than the individuals they trade with directly. When looking at contracting in multiplication, information supplied from an actor who has no stakes in the transaction brings about expedient trust. This type or amount of trust is sufficient to stipulate contracting between parties that initially have very asymmetric information. We suspect credible production of information can compensate for the negative effects asymmetric information would have otherwise. In an environment involving trust between the individuals engaging in the relevant activities, symmetric information distribution of simple performance measures seems unnecessary for the technical process (Braun 2020) but suffices to speed up the breeding process itself by preempting distribution of new variety material, thereby bringing about shorter innovation cycles within the whole system.

Need for resilient breeding systems

As a scientific community, we need to be capable of comparing our cases on the governance of different agricultural SESs to form a reasonable knowledge base for constructing better heuristics for their governance. Darnhofer et al. (2010) advocate that the resilience concept should be used as a heuristic for governance of agricultural systems. Others have called for predictive models as policy-informing tools for governing SESs under the premise of "resilience from what to what" (Carpenter et al. 2001). There is already ample literature on how to frame agroecosystems for farming and how to measure their resilience (Cabell and Oelofse 2012, Rasch et al. 2017). So far, breeding systems have not gained the same kind of attention. The presented governance challenges, however, show that breeding systems, although in some subunits are very similar to a farming system, are substantially different.

Mid-range theories on social-ecological systems

Nonetheless, we want to caution our readers: providing heuristics for robust governance of seed systems in the future is not achieved by merely putting variables into the SESF. We need theory to interpret the relationship of those variables. For example, if the information provided to actors needs to be of a certain type to activate or channel a coordination mechanism, such as a seed market, into a more sustainable direction, then providing additional information through public trials would have advantageous effects according to our hypothesis. If we take the production of more pest-resistant varieties, then it is vital that public trials show counterfactual variants of varieties with no pesticide application to show the reliability of the varieties' resistance traits. However, if the current system were changed to abolish or reduce the trials, this would hamper the credibility of information and thereby negatively influence the introduction of new resistant cultivars.

For developing mid-range theories (Meyfroidt et al. 2018, Cumming et al. 2020) for breeding SESs, further cases of different types of grains, legumes, fruit trees, and other crops would have to be analyzed and subsequently synthesized into a sectoral SESF for breeding systems. We propose further synthesis to produce such a sectoral SESF for the plant breeding sector; for the sake of brevity, we would call it "seed SESF". A seed SESF may highlight variables that are unique but essential for plant breeding systems in general (Partelow 2018) and develop diagnostic theories (Poteete 2010:233) to govern plant breeding successfully. Scientists may develop better heuristics for governance—as demanded by Darnhofer et al. (2010)—for breeding systems, which are easy for policy-makers and other stakeholders to use and understand. Adapting current rules, norms, and strategies to

future challenges in breeding, with a robust knowledge of mechanisms and attributes of the complex adaptive system at hand, will be crucial for the future resilience of all agricultural systems.

CONCLUSIONS

We illustrated how the SESF can be used to analyze the different action situations of the seed-producing system. Complemented by economic theories, we identified the governance challenges arising from social dilemmas in providing varietal and genetic diversity. Our qualitative findings in conjunction with our theoretical underpinnings allow us to hypothesize on the relationship between information provisioning and trust of actors in engaging in coordinating mechanisms, which distribute the seed and breeding material.

For the German case of winter wheat, all action situations coordinate transactions of seed material and property rights. The transaction relationships depend on information on the agronomic performance of varieties, which in turn are contingent upon ecological conditions of the resource systems producing them. Producing and distributing credible information on the agronomic performance of varieties to all actors directs the activities in the breeding system. There are varying kinds of asymmetric information between the different actors (breeding) or actor groups (multiplication and farming) in the action situations. According to the employed theories in these settings, these asymmetries would lead to adverse effects in outcomes. We found, however, that the same types of governance processes facilitated different kinds of trust between the stakeholders, thereby compensating for lack of information to sustain smooth functioning of the overall system.

In subcontracting multiplication and retailing of seed, the governance challenges are to advance symmetric distribution of information between actor groups. In subcontracting, trust between the breeding firm and multiplying actors is an expedient relationship. Individuals count on the other party behaving without guile because this would lead to termination of business relationships or ex post moral hazard on both sides. In farming, no trust is necessary to facilitate buying seed. Farmers are inclined to trust the public information system on agronomic performances of varieties and not the retailers' recommendation. In breeding, the governance challenge of providing genetic diversity to a common pool is to symmetrically distribute public information within the group of actors—breeders—to ease collective action. Individual breeders trust each other with their breeding material, such that the relationship among them is based on the judgment of the individual and on their reputation in the community, yet, this is a lengthy process. State information provisioning speeds up the innovation processes in breeding overall.

Credible information provided by the governance system may substitute for the intensity of trust and entanglement needed to cooperate. As we see from this case, provisioning of public trial information is vital for maintaining genetic and varietal diversity in crops. While this hypothesis needs further testing on its details in other contexts of breeding, we view this insight as relevant to future regulations and public investment. For example, when we talk about allotting funding for field trials in individual states, we see that our findings would advocate for investing in these state trials, such that their quality and credibility is maintained, and information stays publicly accessible in the future.

Responses to this article can be read online at:
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Data Availability:

Because the field notes and other case material cannot in their entirety be anonymized or pseudonymized, they will not be available for sharing. We encourage interested readers to contact the corresponding author, M.K.G., to discuss the article content and qualitative coding procedures. All three authors are employed by a publicly funded German University and must comply with General Data Protection Regulation (EU) 2016/679 and German data protection standards. The concrete processes and regulations of the University of Bonn apply here and can be requested from the data protection office of the University of Bonn (https://www.datenschutz.uni-bonn.de/de).

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Appendix 1

Figure A1.1: Second-tier SESF components for provisioning and appropriating genetic diversity in German winter wheat

Pre-breeding system (PB-RS) †		Governmental resource system (G-RS) †			Breeding firms resource systems (BF-RS) †		Governance system (GS) †	
PB-RS1	Public and private seed sector	G-RS 1	Public sector		BF-RS1	Seed sector	GS1	Breeders rights
PB-RS2	No clear boundaries	G-RS 2	Clear boundaries		BF-RS2	Heterogenous by firm	GS2	Germany as part of EU
PB-RS3	Big	G-RS 3	Testing sites		BF-RS3†	Heterogenous size of nurseries	GS3	All plant breeders
PB-RS4	Nurseries and screening facilities	G-RS 4	Nurseries and facilities for evaluation of trials		BF-RS4†	Facilities for phenotypic and genotypic evaluation	GS4	Democratic
PB-RS5	-	G-RS 5	All Varieties on DVL	Lines in VCU testing	BF-RS5	Number of lines submitted for approval	GS5	Legislative branch of government (EU-level/National legislation); Lobbying organizations
PB-RS7	-	G-RS 7	-	-	BF-RS7	Fairly predictable	GS6	Operational-choice rules and collective-choice rules under constitutional-choice rules
PB-RS8	Medium	G-RS 8	Not existent	Not exsistent	BF-RS8	Medium	GS7	Private and common property side by side
PB-RS9	Globally spreadout	G-RS 9	-	6 trial sites over Germany	BF-RS9†	Heterogenous by firm locations in Germany and worldwide	GS8	Multiple norms and strategies within community

Pre-breeding Material (PB-RU) †		DVL Varieties (G-RU)			Breeding Firms' Systems (BF-RU) †		Breeders (B-A) †	
		Approved (G-RUa) †		Pre-approved (G-RUb) †				
PB-RU1	-	G-RU1	Mobile	Immobile with exceptions	BF-RU1	Immobile with exceptions	B-A1	19 winter wheat breeders
PB-RU2	-	G-RU2	Number of new varieties per year	Number of submitted lines per year	BF-RU2	Heterogenous per firm	B-A2†	Heterogenous depending on firm size
PB-RU3†	High	G-RU3†	Low - medium	High	BF-RU3†	High	B-A3	Experiences with own material and varieties important for usage
PB-RU4	Very high; invaluable	G-RU4	-	-	BF-RU4	Heterogenous per variety	B-A4	Heterogenous locations in Germany and worldwide
PB-RU5	Heterogenous	G-RU5	All varieties in DVL	Number of lines in VCU testing	BF-RU5	Heterogenous per firm	B-A5	Enterpreneurial
PB-RU6	Heterogenous	G-RU6†	Name of variety; DUS results	VCU testing results of lines submitted	BF-RU6	Labels applied within nursery	B-A6†	Partially very strong trust & reciprocity relationships
PB-RU7b	Programs in Germany & worldwide	G-RU7b	Spread over Germany	VCU testing sites in Germany	BF-RU7b†	Material within nurseries	B-A7	Heterogenous mental models per breeder determined by incomplete information
PB-RU7a	Since 1960's	G-RU7a	Number of varieties approved each year	Three years of VCU testing	BF-RU7a	Each year resown according to plan	B-A8	Very high resource dependent
							B-A9†	Hetergenous per firm

Action situations appropriation and provision of genetic diversity

Interactions (GD-I)		Outcomes (GD-O)	
GD-I1†	Levels of usage of material	GD-O1 †	Efficient use of genetic traits
GD-I2a†	Information sharing	GD-O2 †	Sustained German gene pool
GD-I2b†	Material sharing	GD-O3	-
GD-I2c†	Nursery space sharing		
GD-I5†	Investments in joined R&D projects		
GD-I7 / GD-I8 †	Networking - common activities in R&D projects		

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. VCU denotes value of cultivation and use testing. DVL means the Descriptive Variety List. DUS denotes distinctiveness, use and stability testing. Relevant sources for the included variables were mainly interviews 1, 2, 3, 7, 8, 10, 12-15, 17-20, 22, 24-30, and 32; see list appendix 2 table 1. † marks those variables used in the main text.

	Governmental resource system (G-RS)			Breeding firms resource systems (BF-RS)			Multiplication system (M-RS)			Governance system (GS)	
G-RS1	Public sector			BF-RS1	Seed sector		PB-RS1	Seed sector		GS1 †	Breeders rights and Seed regulations
G-RS2	Clear boundaries			BF-RS2	Heterogenous depending on firm		PB-RS2	Clear boundaries		GS2	Germany
G-RS3	Testing sites and respective sites for testing available			BF-RS3	Heterogenous size of nurseries		PB-RS3	Size of multiplier		GS3 †	All plant breeders and multiplication organisations, multiplying farmers and certification organisations for seed
G-RS4	Nurseries and facilities for evaluation of trials			BF-RS4	Heterogenous facilities for phenotypic and genotypic evaluation		PB-RS4	Fields multiplication		GS4	Democratic
G-RS5	All varieties on DVL		Lines in VCU testing	BF-RS5	Number of lines submitted for approval		PB-RS5	Propagation area for the crop		GS5	Legislative branch of government
G-RS7	Predictable variety performance			BF-RS7	Fairly predictable		PB-RS7	Heterogenous per variety		GS6	Operational-choice rules and constitutional-choice rules
G-RS8	-		-	BF-RS8	Minimal		PB-RS8	Medium		GS7 †	Private property system
G-RS9 †	State variety trials in different regions		6 trial sites over Germany	BF-RS9	Heterogenous locations in Germany and worldwide		PB-RS9	Hetergenous within regions		GS8	Multiple norms and strategies

	DVL Varieties (G-RU) Approved (G-RUa) †	Pre-approved (G-RUb) †		Breeding Firms' Systems (BF-RU)			Multiplied Material (M-RU)			Breeders (B-A)			Multipliers (M-A)	
G-RU1	Mobile	-		BF-RU1	Mobile		M-RU1	Mobile		B-A1	19 Winter wheat breeders		M-A1	Oligopoly to polypoly
G-RU2	Number of new varieties per year	Number of submitted lines per year		BF-RU2	Heterogenous per firm		M-RU2 †	For winter wheat the multiplication factor is 1:40		B-A2	Heterogenous depending on firm size		M-A2	Heterogenous depending on firm size and type
G-RU3	-	-		BF-RU3	-		M-RU3	-		B-A3	Experiences with own material and varieties important for usage		M-A3	Experiences with kinds of varieties sold
G-RU4	Predictable if in state trials			BF-RU4	Heterogenous per variety		M-RU4	Heterogenous per variety		B-A4	-		M-A4	Located in different regions
G-RU5	All varieties in DVL	Number of lines in VCU testing		BF-RU5	Heterogenous per firm		M-RU5	Heterogenous per multiplier and region		B-A5	Entrepreneurial		M-A5	Entrepreneurial
G-RU6	Name of variety & DUS results	VCU testing results of lines submitted		BF-RU6	Variety names applied to lines		PB-RU6	Variety names; VCU qualitities		B-A6	-		M-A6	-
G-RU7b	-	VCU testing sites in Germany		BF-RU7b	-		M-RU7b	-		B-A7	Heterogenous mental models per breeder determined by incomplete information		M-A7	Mental models of SES and heuristics for devising multiplication areas
G-RU7a	Varieties approved each year	Three years of VCU testing		BF-RU7a	-		M-RU7a	Propagation each year		B-A8	High resource dependence		M-A8	High resource dependence
										B-A9	-		M-A9	-

Action situations for providing varietal diversity

Interactions (PV-I)		Outcomes (PV-O)	
PV-I1 †	Levels of usage of varieties in propagation	PV-O1 †	Supply of diverse varieties fitting farmers preferences
PV-I2a	Public provision of information on trial results	PV-O2 †	Ecological Performance – outcomes of VCU and FSV trials in different regarding yield and other qualities of a variety
PV-I3	Heuristic deliberation of multipliers	PV-O3	-
PV-I5 †	Investment in promising varieties		
PV-I10	Multipliers evaluate VCU and state trials results; are being quality checked		

Figure A1.2: Second-tier SESF components for provisioning varietal diversity in German winter wheat

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. Relevant sources for the included variables were mainly interviews 1, 2, 3, 4, 6, 8, 9, 14, 21, 23, and 33; see list appendix 2 table 1. † marks those variables used in the main text.

	Farming system (F-RS)		Multiplication and retailing system (M-RS)		Governance system (GS)
F-RS1	Agricultural sector/ wheat cropping	M-RS1	Seed sector	GS1 †	Seed regulations
F-RS2	Per farm clear boundaries	M-RS2	Clear boundaries	GS2	Germany
F-RS3	Heterogenous per farm	M-RS3	Heterogenous	GS3 †	Multiplication organizations, multiplying farmers and certification organizations for seed, all agricultural retailers
F-RS4	Fields and grain storage facilities	M-RS4	Fields multiplication, storage facilities for seed	GS4	Democratic
F-RS5	Harvest per hectare	PB-RS5	Heterogenous per propagation area for the crop/variety	GS5	Legislative branch of government
F-RS7	Dependent on biotic and abiotic factors & variety	PB-RS7	Heterogenous per variety	GS6	Operational-choice rules and constitutional-choice rules
F-RS8	Usually available	PB-RS8	High	GS7 †	Private property system
F-RS9	Spread throughout Germany	PB-RS9	Heterogenous within regions	GS8	Multiple norms and strategies

	Seed (F-RU)		Multiplied material (M-RU)		Farmers (F-A)		Multipliers and retailers (M-A)
F-RU1	Mobile	M-RU1	Mobile	F-A1	Polypoly	M-A1	Oligopoly
F-RU2	1:40 reproduction coefficient	M-RU2	Heterogenous per variety	F-A2	Heterogenous depending on firm size	M-A2	Heterogenous depending on firm size and type
F-RU3	-	M-RU3	-	F-A3	Experiences with varieties	M-A3	-
F-RU4	Heterogenous per farm (EU avg 50€/ha)	M-RU4	Heterogenous per variety	F-A4	Spread over different regions with various density	M-A4	Located in different regions
F-RU5	-	M-RU5	Heterogenous per multiplier and region	F-A5	Entrepreneurial	M-A5	Entrepreneurial
F-RU6	Heterogenous attributes per variety and per field	M-RU6	Variety names; public trial results	F-A6	-	M-A6	-
F-RU7b	Varieties in farmers fields	M-RU7b	Multipliers fields within regions; local storage facilities of retailers	F-A7	Heterogenous mental models per farmers determined by different heuristics and social networks	M-A7	Mental models of SES and heuristics for devising multiplication areas
F-RU7a	Depending on crop rotation schemes	M-RU7a †	Each year propagation according to predicted demand	F-A8	High resource dependence	M-A8	High resource dependence
				F-A9	Heterogenous per farm	M-A9	-

Action situations for appropriating varietal diversity

Interactions (AV-I)		Outcomes (AV-O)	
AV-I1	Varieties being bought / farm-saved with license	AV-O1 †	Sustained farming with appropriate varieties; economic and social viability of farm
AV-I2 †	Information provided by federal/ state variety trials	AV-O2 †	Farmers find appropriate variety for their biotic and abiotic circumstances
AV-I3 †	Deliberation on future variety performance by farmers	AV-O3	Externalities - agricultural system in terms of soil qualities (N), biodiversity outcomes (affected by pesticide/herbicide use), water quality
AV-I5 †	Choice of farm-saving or buying certified seed		
AV-I7 /I8	Networking with farmers and between farmers informs variety choice		
AV-I9	Farmers monitor their variety performance individually		
AV-I10	Farmers evaluate their variety performance individually		

Figure A1.3: Second-tier SESF components appropriating varietal diversity in German winter wheat

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. Relevant sources for the included variables were mainly interviews 4, 5, 9, 11, 8, 16, 21, 23, 31, and 33; see list appendix 2 table 1. † marks those variables used in the main text.

Appendix 2

Table A2.1 Listing of interviews and participatory observations

Number	Kind	Position / Organization / Occasion	Topic	Time
1	OI	Head of breeding program (private)	Breeding business overview	Feb 16
2	OI	Head of breeding program (private)	Breeding business overview	Apr 16
3	OI	Product manager	Selling seed to multipliers	Apr 16
4	SI	Multiplying farmer / farmer	Variety choice and farming	Apr 16
5	OI	Farmer	Plant protection	Apr 16
6	PO	Meeting sales management btw. breeding and multiplication firm	Selling seed to farmers	Mar 17
7	PO	Plant breeders' rights admission meeting	Plant breeders' rights admission	Mar 17
8	PO	Head of breeding program/head of sales	Variety admission	Mar 17
9	OI	Public breeder	State Variety Trials	Mar 17
10	PO	Plant breeders in training	Plant breeding general	Apr 16
11	PO	Farmer	Inspecting winter wheat	Apr 16
12	OI	Public breeder	Prebreeding	Apr 16
13	PO/OI	Public breeder	Back-crossing	Apr 16
14	PO	Public breeder	Hybrid breeding	Jun 16
15	PO	Plant breeders in training	Double-haploids	Jun 16
16	S	DLG-Field days	Farming winter wheat and plant protection strategies	Jun 16
17	PO	Public breeder	Field inspection	Jun 16
18	PO	Plant breeders in training	Tubers and mutation breeding	Jun 16
19	PO	Breeding assistant (private firm)	Crossing	Jun 16
20	PO	Plant breeders in training	Field inspection	Jun 16
21	PO	Plant breeders in training	Seed certification	Jul 16
22	OI/PO	Public breeder	Population breeding	Jul 16
23	PO	Meeting state variety recommendation announcements	State variety recommendation announcements	Aug 16
24	SI	Scientific plant pathologist from a University	Resistances, farming behavior and breeding	Mar 16
25	SI	Public breeder	Worldwide prebreeding	Jun 19
26	PO	Public breeder	Selection early generations	Jul 16
27	PO	Head of breeding program (private)	Planning of crosses	Feb 17
28	PO	Public breeder	Field inspection prebreeding	Jun 16
29	PO	Private breeders	Field inspection and new technologies	Jun 19

30	PO	Head of breeding program	Selection of later stage generations	May 17
31	PO	Talk in expert panel for breeders	Farmers demands on breeding goals	May 17
32	OI	Researcher at LFL	Maintenance breeding	Apr 16
33	SI*	Head of breeding program (private)	Variety pricing	Dec 17
34	SI*	Head of breeding program (private)	Variety pricing	Dec 19
35	PO	Farmer	Plant protection heuristics	Jun 19
36	OI	Cereal researcher at LFL	Breeding system	Mar 16
37	OI	Researcher in crop pathology	Host-pathogen-human interactions in cereal cropping	Sep 16
38	OI	Researcher at Julius-Kühn Institut	Resistance breeding wheat diseases	Mar 17
39	OI	Researcher at Julius-Kühn Institut	Phytopathology	Jan 16

OI = Interview; SI = Semi-structured Interview; PO = participatory observation; S = survey

*Brief conversation with only field notes available